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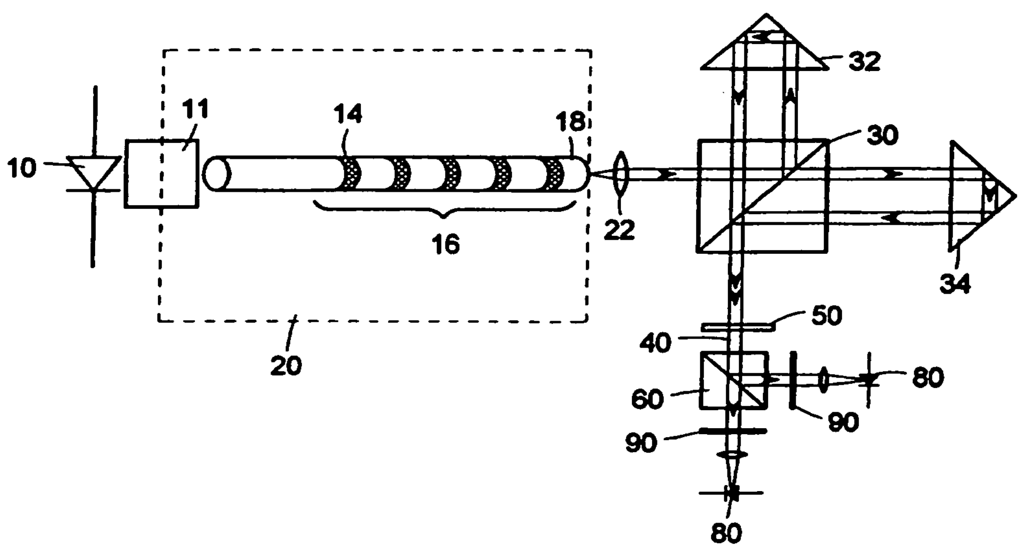

(57) Abstract

A narrow frequency bandwidth/high coherence laser light source is created by launching light from a laser diode (10) into a monomode optical fibre (12) containing a Bragg grating (16), made up of regions of fibre (14) of higher refractive index. The extent of the fibre from the laser up to, and including the grating (16) is retained within a temperature controlled cavity (20), preventing alterations in the pitch of the grating, or its separation from the laser due to thermal expansion. The grating is created by means of the exposure of the fibre to a periodic ultra violet pattern, which is in turn created by passing U.V. light through a phase grating. During manufacture, the output wavelength of the laser, and grating pitch and separation of the grating from the laser are matched, and the extent of the reflectivity of the grating (16) is then adjusted in dependence upon the coherence of light transmitted through the grating (16).

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LOW FREQUENCY BANDWIDTH LASER

The present invention relates to a laser, such as a semiconductor laser diode ("laser") having a narrow frequency bandwidth, and which may be used, for example, in interferometry to enable measurement of a displacement.

Laser diodes are known to emit laser light over a relatively wide frequency bandwidth. A consequence of this is that light emitted from the diode will not have the same phase, at least to the accuracy, and over distances which are required in interferometry. The diode is thus said to have a short "coherence length". The present invention relates to a technique whereby the coherence length of e.g. a laser diode may be increased to the extent that the diode may provide light which is useful for interferometric purposes.

A first aspect of the present invention provides for an increase in the coherence length of a laser by coupling to the laser a substantially monomode optical fibre which contains a grating in the form of a plurality of longitudinally spaced fibre regions having a refractive index which differs to that of the fibre core, the fibre regions being spaced apart by a distance corresponding to the desired wavelength of emission from the diode, and wherein the fibre is retained within a temperature controlled cavity.

In operation, when the laser emits a relatively broad frequency/wavelength band of light, the grating selectively reflects a relatively narrow frequency/ wavelength of the emitted light back into the laser, which will in turn result in the laser lasing about a frequency bandwidth centralised upon the frequency corresponding to the wavelength of the reflected light, thus achieving a reduction in the frequency bandwidth of the diode.

Typically, a fibre having regions of higher refractive index is manufactured by exposing the relevant regions of the fibre to incident ultraviolet light. A second independent aspect of the invention provides a method of adjusting the coherence of light from a light source, the light source being provided by light launched from a laser into an optical fibre and passing out of an end of the fibre distal to the laser, the method comprising the steps of:

(a) illuminating the fibre with light thereby to create at least one fibre region having reflective properties within the fibre;

(b) monitoring the coherence of light from the source;

(c) adjusting the reflectivity of the at least one region in the fibre; and

repeating steps (b) and (c) until the coherence of light from the source is as desired.

Embodiments of the invention will now be described, by way of example, and with reference to the accompanying drawings, in which:

Fig 1 is a schematic view of a linear displacement laser interferometer employing a laser diode stabilised in accordance with the present invention;

Fig 2 is an oscilloscope display;

Fig 3 is a schematic representation of a method of creating a grating in a fibre;

Figs 4A-D illustrate the manufacturing process shown in Fig 3; and

Fig 5 is a further oscilloscope display.

Referring now to Fig 1, a linear displacement laser interferometer includes a laser diode 10, which generates an output beam of linear polarised laser light. The output

beam is launched, via suitable optical coupling 11, into a substantially monomode optical fibre 12, having a plurality of microscopic regions 14 whose refractive indices differ to that of the remainder of the fibre (typically up to a difference in refractive indices of about 1 part in 10000); in the present example they have a higher refractive index. The regions 14 are spaced apart by a distance corresponding to the desired output wavelength of the laser diode and are referred to collectively as a "grating" 16. The fibre 12 is retained in a temperature controlled cavity 20, to prevent variations in the distance between the regions 14 of the grating. The fibre 12 and grating 16 operate to stabilise the frequency of light emitted from the diode (which is itself temperature controlled), and to reduce the frequency bandwidth over which light is predominantly emitted. When (as a result of what is essentially a random emission of frequencies from the diode) the diode emits a wavefront of light of the desired output wavelength, a proportion (which depends upon the difference in refractive index between the main body of the fibre 12 and regions 14) of the wavefront is reflected at the grating 16. This is because the pitch of the grating is the same as the wavelength of the light of the wavefront. The reflection of part of this wavefront will result in the diode emitting a greater proportion of photons with the requisite frequency/wavelength, and the bandwidth of the emitted light being reduced, and centralised about the desired frequency/wavelength. Temperature control of the fibre 12 prevents variations in the length of the fibre (c.f. the size of a "laser cavity"), and also the spacing between regions 14 (which would alter the wavelength of light reflected at grating 16 leading to a change in wavelength of the laser light emitted).

Light from the emission end 18 of the fibre is collimated by means of a lens 22, and is subsequently incident upon a polarising beamsplitter cube 30, oriented at 45° to the direction of polarisation of the laser light. A fraction

of the incident beam is reflected at the beamsplitter 30 into a retroreflector 32, mounted in a stationary position with respect to the beamsplitter 30, and which in conjunction with the beamsplitter 30 forms a reference arm of an interferometer. The fraction of the light beam which passes undiverted through beamsplitter 30 is incident upon a further retroreflector 34, mounted to an object whose linear displacement with respect to the beamsplitter it is desired to determine and which forms the measurement arm of the interferometer. Light reflected at retroreflectors 32,34 is recombined at the beamsplitter 30, and, after passage through a ¼ waveplate 50, interferes to generate an interference beam 40.

The interference beam 40 is incident upon a non-polarising beamsplitter cube 60, which splits interference beam 40 into two fractions, each of which are incident upon a photodetector 80 via polaroids 90, which select different phases (e.g. 0° and 90°), of interference beam 40.

Movement of the retroreflector 34 in the direction of the undiverted light beam will result in a change in the relative optical path lengths of the beams in the reference and measurement arms, which will result in a shift in the interference pattern and a consequent change in the intensity of light incident upon the photodetectors 80. The resulting intensity modulation is transduced into a pair of phase-shifted correspondingly modulating signals at photodetectors 80, from which the displacement of the retroreflector 34 relative to a reference position may be determined.

Typically, the outputs from the photodetectors may be fed to X and Y inputs of an oscilloscope. When the components of the interference beam 40 incident upon the two photodetectors 80 are equal in amplitude (over a cycle), have a phase difference of 90° (known as quadrature), and are coherent, the trace on the oscilloscope is a circular

Lissajous, with a well defined line (as shown in Fig 2) which may be used to generate a value representing the displacement of the movable retroreflector.

Coherent component beams of the interference beam 40 are generated, as described above, by means of the reflection at grating 16 of a selected frequency/wavelength of the laser light emitted from the diode. The degree of frequency/wavelength selectivity, and the extent to which the grating 16 reflects the selected frequency/wavelength light determine the magnitude of the frequency bandwidth (i.e. coherence length) of light emitted. The frequency/wavelength selectivity may be determined by the geometry of the grating 16, or alternatively by some external control of the operating characteristics of the laser, such as (in the case of a laser diode) the drive current and/or operating temperature. The reflectivity is determined by the number of regions 14 of higher refractive index and/or the extent to which their refractive index differs with respect to the refractive index of the fibre core ("Δn").

To enable the grating 16 in the fibre to have the maximum effect upon the coherence length of the laser light, the frequency/wavelength of the laser light and the geometry (e.g. pitch of the refractive regions) of the grating must be matched. This can be achieved either by adjusting the frequency/wavelength of the output beam, or the pitch of the grating 16 relative to the laser (as will be described later). If a particular frequency/wavelength of light is required, then the grating pitch will need to be matched to the desired frequency/wavelength; if the precision of the emitted frequency/wavelength is not an issue, the laser output may be adjusted so that it matches the grating characteristics. In addition, for correctly matched laser and grating characteristics the following conditions must be satisfied: (i) the distance between the grating 16 and the rear reflective face of the laser must be a half

integer multiple of the desired wavelength; and (ii) the distance between reflective faces of the laser must be a half integer multiple of the desired wavelength. As previously these conditions can be met by either adjusting the output frequency/wavelength of the laser, or the position of the grating 16 relative to the laser.

Given adequately matched laser frequency/wavelength, and grating pitch and position, it is important that the correct amount of light is reflected by the grating 16; if too little light is reflected the bandwidth of the laser will not narrow sufficiently, while if too much light is reflected the diode will go into "multimode" operation and emit light over a very broad spectrum. It is therefore important to adjust the reflectivity of the grating 16 so that the appropriate amount of light necessary to achieve the required coherence length is reflected by grating 16. This can, in theory, be done either by adding or subtracting regions 14 to and from the fibre 12, or by increasing and decreasing the refractive index of these regions 14. In practice, regions 14 of higher refractive index are created by exposure to U.V. light; the extent of exposure to a given intensity of light determining the refractive index. The addition of further regions 14 is a relatively expensive solution, since these further regions must be created at locations which are spaced extremely accurately from all the other regions. Our preferred method is to expose the fibre 12 to a given intensity of a periodic pattern of U.V. light to create grating 16, then to test the coherence length of the laser and subsequently adjust the reflectivity by means of further exposure as necessary.

Techniques for exposing fibres to create a grating are known per se, and one such technique, illustrated in Fig 3 involves directing a beam of U.V. light through a phase grating to create an interference pattern in which the fibre 12 is positioned.

Referring now to Figs 4A-D, this process will be explained more fully. Exposure of a plurality of fibre regions 14 to a periodic intensity distribution of U.V. light will result in the light conductive core 100 of the fibre having a variation in refractive index substantially as illustrated in Fig 4B. Because the difference in refractive index between exposed and unexposed parts of the core 100 (i.e. Δn) must be smaller than the difference in refractive indices of the core 100 and cladding 110, the value of Δn is such that very little reflection will take place at an individual region 14. It is for this reason (among others) that a plurality of such regions are required in the form of a grating 16 i.e. to produce the requisite total reflectivity. It should also be noted that the susceptibility of the fibre core 100 to a change in refractive index as a result of the incidence of U.V. light is non-linear. That is to say that a completely unexposed fibre will initially undergo a relatively rapid rate of change of refractive index upon exposure to U.V., but that the rate of change of refractive index with incident U.V. intensity will subsequently be lower.

Referring now to Fig 4C, a consequence of this is that a grating which has been created within a fibre may be erased, substantially or in part, by exposing the entire grating region to U.V. light. During such an exposure, the previously unexposed regions of the fibre will undergo a more rapid increase in refractive index than those which have previously been exposed, thereby enabling the entire region of the grating to be "washed out" to a constant refractive index after a given exposure time. This phenomenon is illustrated in Fig 4C, whereby a short exposure of U.V. light in the entire grating region results in a significant reduction in the value of the parameter $\Delta n'$ (the difference between the refractive index of a fibre region 14 and a region of the fibre which lies within the grating 16 immediately after such a region 14). Furthermore, since the value of Δn is small, and no

significant reflection will take place at a single region 14, the removal, or washing out (once it has occurred), of a grating in this fashion has no significant effect on the subsequent transmission of laser light along the fibre, because no significant reflection takes place at the single location 16' along the fibre core where the stepped increase in refractive index takes place. This means that once a grating has been washed out, a further grating may be created in the region of the previously washed out grating. This is the case even though the new grating lies within a region of the fibre core 100 which has a higher fundamental refractive index than that of the rest of the fibre core 100. A newly created grating, located on the site of a washed out grating is illustrated in Fig 4D.

As mentioned above, fundamentally two factors need to be taken into consideration in attempting to use a grating 16 within an optical fibre to provide a stable coherent laser source: a matching of the output wavelength with the grating position and pitch; and the degree of reflectivity of a appropriately matched grating. Typically, during manufacture the characteristics of the laser and the grating geometry/position will first be matched. This is done by creating a very weak grating within the fibre at what is calculated to be an appropriate location, and investigating the coherence of the output laser source as a result. If it is required to change the pitch of the grating, this may be performed by washing out the existing grating, and creating a further grating with a different pitch (the pitch of the gratings being changed as a result of a corresponding alteration in the mutual angles of incidence of the interfering U.V. beams). When the grating and laser characteristics are matched, a step-change in the coherence of the output laser will result. Matching of laser wavelength and grating pitch is performed by adjusting either the grating pitch (as explained in relation to Figs 4C and 4D above), and/or the drive current and/or operating temperature of the laser diode. Once the

laser and grating characteristics have been matched, adjustments may then be made (either to increase or decrease) to the reflective property of the grating 16 by changing the extent of exposure of the regions 14 of the grating 16 to U.V. light as described above. The process of adjusting the reflectivity of the grating is repeated until the requisite coherence length has been attained.

The coherence length may be determined by means of an oscilloscope. The trace on an oscilloscope due to microscopic movement of the retroreflector 34 (e.g. due to air turbulence) can be seen in Fig 4. This trace represents a fraction of a circular arc. It can be seen that the line defining the segment of the arc is relatively thick and ill-defined, representing a short coherence length for the laser diode 10 (by contrast to the "ideal" trace shown in Fig 2). The fibre 12 is thus repeatedly exposed to the U.V. interference pattern until the oscilloscope trace becomes sufficiently well-defined; representing an acceptable signal as a result of the incidence of an interference beam formed from coherent component beams.

The present has been exemplified by using regions of differing refractive index to cause reflection in the fibre. Any one or more fibre regions which have a reflective effect on light transmitted along the fibre should be regarded as lying within the scope of the invention, irrespective of their refractive index or indices.

CLAIMS

1. A method of adjusting the coherence of light from a light source, the light source being provided by light launched from a laser into an optical fibre and passing out of an end of the fibre distal to the laser, the method comprising the steps of:

(a) illuminating the fibre with light thereby to create at least one fibre region having reflective properties within the fibre;

(b) monitoring the coherence of light from the source;

(c) adjusting the reflectivity of the at least one region in the fibre; and

repeating steps (b) and (c) until the coherence of light from the source is as desired.

2. A method according to claim 1 wherein the laser is a laser diode and the method additionally comprises the step of adjusting at least one of the diode's drive current and operating temperature.

3. A method according to claim 1 further comprising the step of adjusting the location of the at least one reflective region relative to the laser.

4. A method according to claim 1 wherein the reflective properties of the at least one region are provided by a change in refractive index of the fibre at the region.

5. A method according to claim 4 wherein the fibre is illuminated with a periodic light pattern to create a grating within the fibre.

6. A method according to claim 5 wherein during

adjustment the reflective property of the grating is increased by further exposure to the periodic light pattern.

7. A method according to claim 5 wherein the method additionally includes the step of adjusting the pitch of the grating.

8. A method according to claim 7 wherein the pitch of the grating is adjusted by means of a corresponding adjustment in the pitch of the periodic light pattern.

9. A method according to claim 8 wherein the periodic light pattern is created by interfering two incident beams, and the pitch of the pattern is adjusted by adjusting their relative angle of incidence.

10. A method according to claim 1, wherein light from the source is used to supply a displacement measuring laser interferometer, the coherence of the light being monitored using a signal which is indicative of a change in optical path length of a measuring arm of the interferometer.

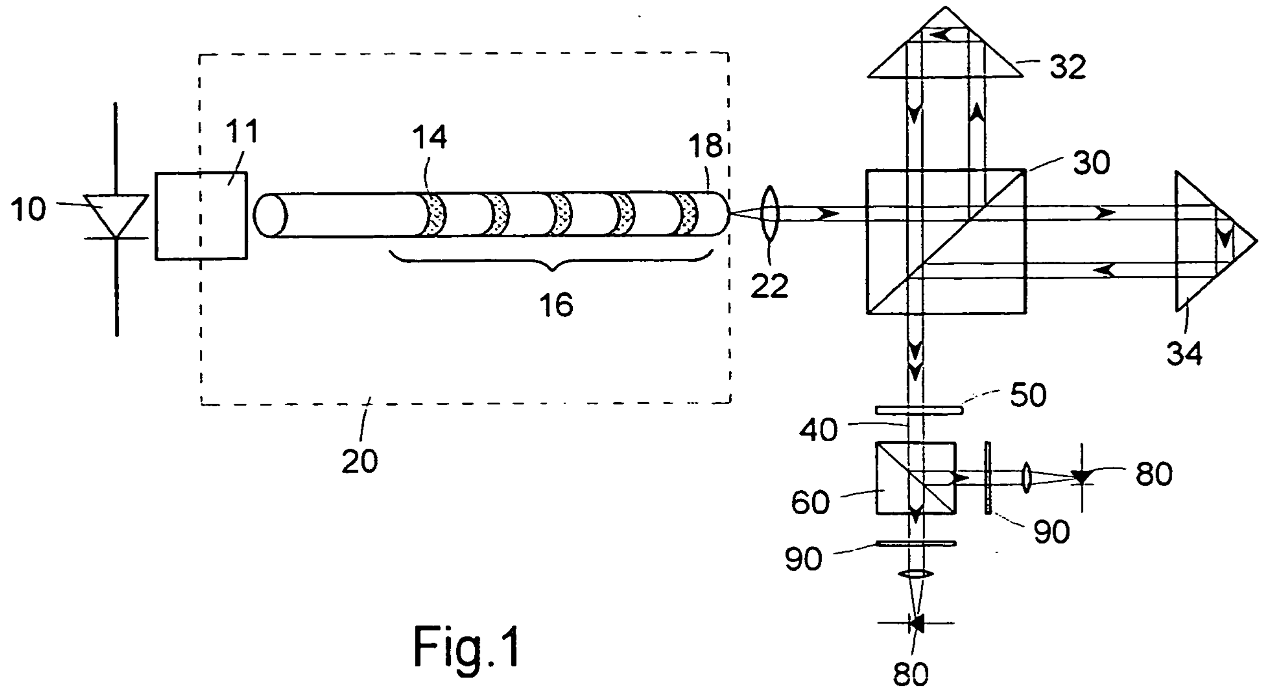

Fig.1

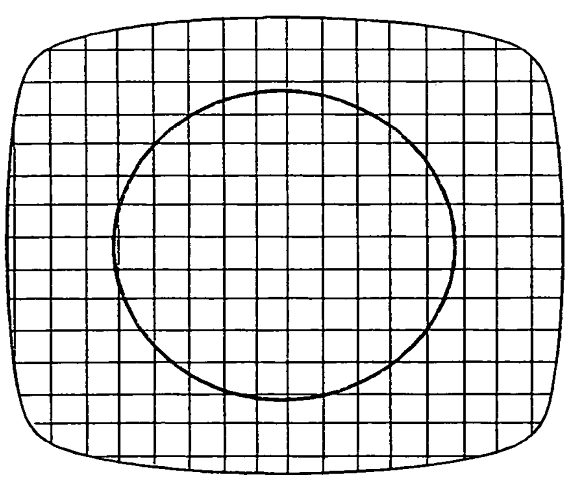

Fig.2

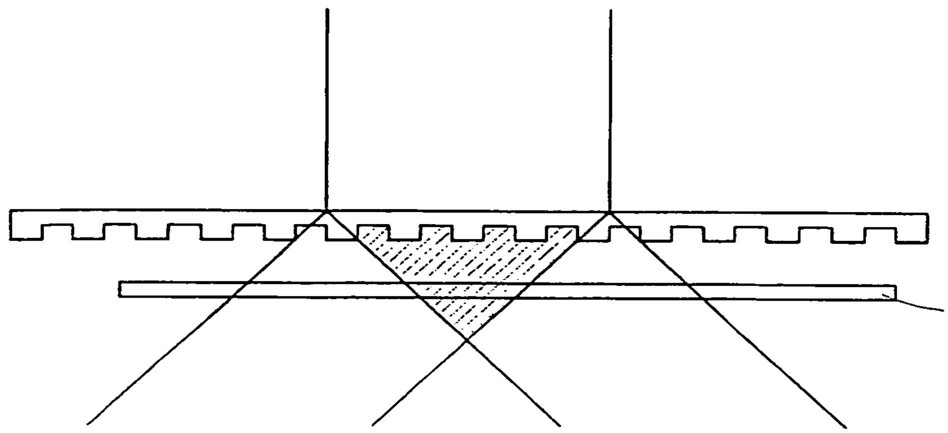

Fig.3

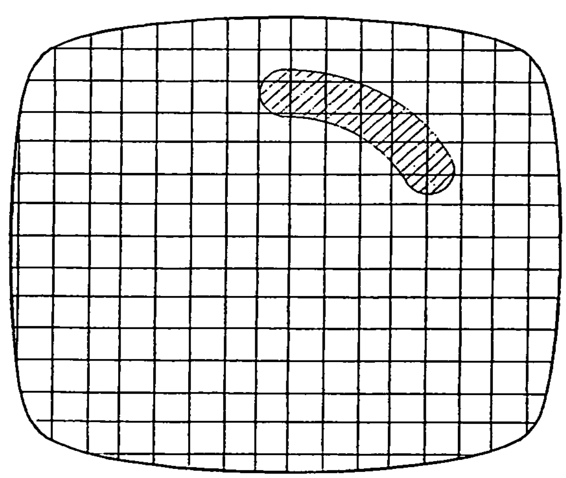

Fig.5

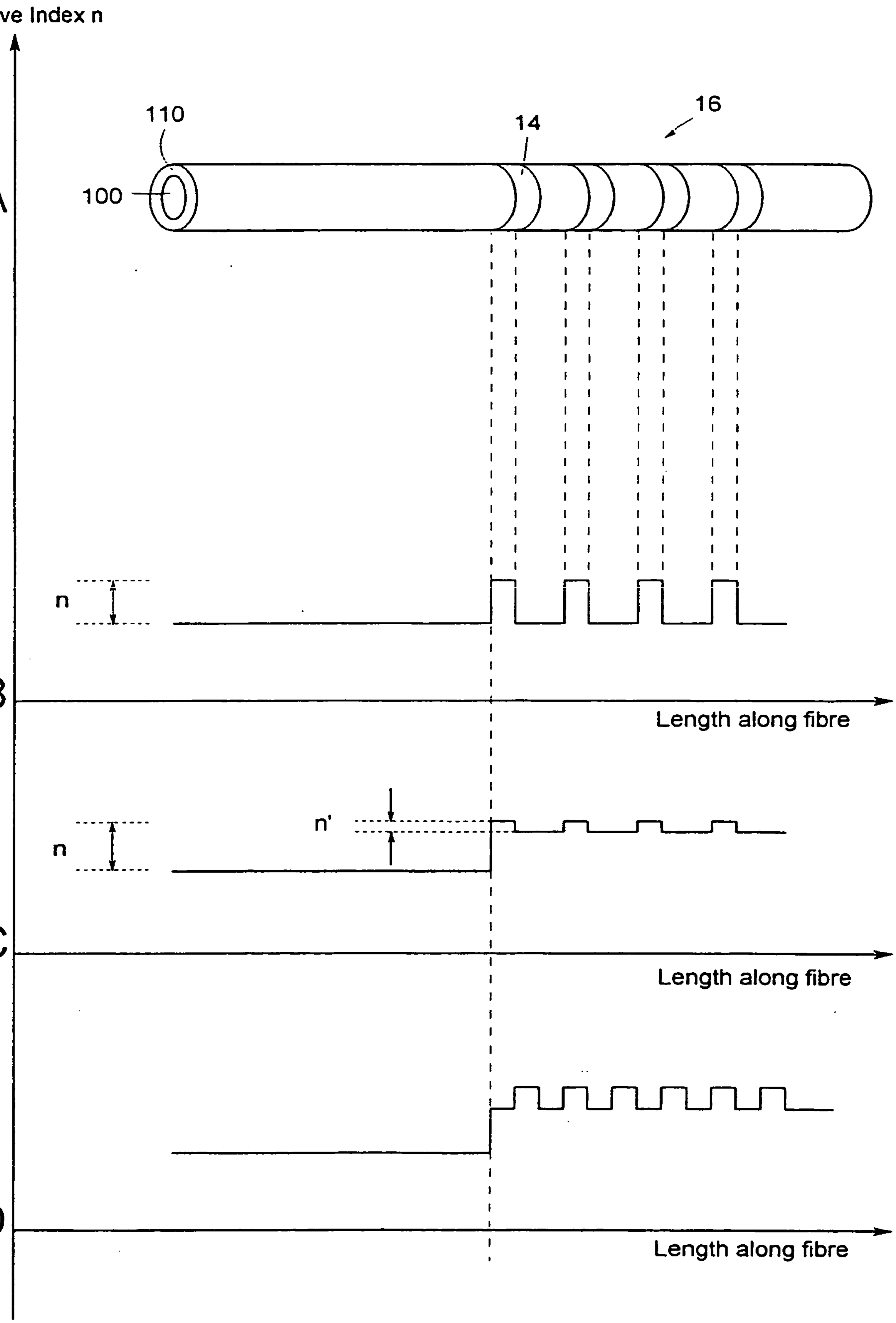

Fig 4A

Fig 4B

Fig 4C

Fig 4D

INTERNATIONAL SEARCH REPORT

International Application No
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A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01S3/085 G01B9/02 H01S3/08 H01S3/1055

According to International Patent Classification (IPC) or to both national classification and IPC

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Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01S G01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	CHRISTENSEN D A ET AL: "LASER DIODE COHERENCE LENGTH VARIATION FOR BALANCING FIBER OPTIC INTERFEROMETERS" OPTICAL ENGINEERING, vol. 33, no. 6, 1 June 1994, pages 2034-2038, XP000454692 see the whole document ---	1,2
A	WO 88 05614 A (HEWLETT PACKARD CO) 28 July 1988 see abstract; figure 1 ---	1

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Inte onal Application No
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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INTERNATIONAL SEARCH REPORT

Information on patent family members

Inte onal Application No
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